TRANSPORT PHENOMENA AND NOISE IN REAL QUANTUM WIRES

FINAL REPORT

by

Vladimir Mitin

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13. ABSTRACT *(Maximum 200 words)*

We have calculated electron scattering by confined LO, localized SO, and bulk-like acoustic phonons in quantum wires (QWIs). We have demonstrated that the role of LO phonon scattering is dominant in a wide range of parameters. The elasticity of acoustic phonon scattering has been a commonly used approximation. Our results demonstrate that electron scattering by acoustic phonons in QWIs becomes essentially inelastic and is an effective mechanism of energy dissipation. We have obtained superlinear electron transport in QWIs at low temperatures. This superlinearity stems from reduction of acoustic phonon scattering efficiency when the electron system is heated. We have discovered a novel effect of negative absolute photoconductivity in QWIs. This effect is caused by strong asymmetry of the electron distribution function due to resonant scattering by optical phonons. We have investigated the role of different phonons on electron transport in QWIs and have found that a square cross-section is optimum for high mobilities. We have calculated nonequilibrium electron noise in QWIs. Our results show that a major noise source in QWIs is electron scattering by acoustic (low field) and optical (high field) phonons. In general, noise in QWIs is essentially suppressed.

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FOREWORD

Low dimensional semiconductor structures have revoliutionized microelectronics. Just a decade ago quantum wells with quasi-two-dimensional electron gas were an object of basic research. Today lasers based on such quantum wells are taking over p-n junction lasers in all branches of industry. Most of our homes utilize such lasers in compact disk players. Quantum wires with quasi-one-dimensional electron gas are still an object of basic research. Their fabrication requires state-of-the-art technology. Nevertheless, we do believe that utilization of QWIs in microelectronics and optoelectronics is not far away. This project was aimed at making it even closer. The aims of the research project have not been modified from original applications. We strongly believe that all major goals of our project are achieved, so that the project is succesfully accomplished.

We are grateful to the United States Army Research Office for opportunity to work in the forefront area of microelectronics and to train students in this area.

1 REPORT OF ACCOMPLISHMENTS

1.1 Problem

The strategic goal of our project was to develop a theoretical background for utilizing quasi-one-dimensional (1D) quantum wire (QWI) structures for microelectronic applications. Any electrical application of semiconductor structure is based on electron transport and noise properties in this structure. QWIs have different band structure and different scattering mechanisms than bulk semiconductors or semiconductor macrodevices. The understanding of scattering mechanisms in QWIs was far from complete at the beginning of our work on this project. Therefore, electron transport and noise in realistic (imperfect, involving multiple subbands, finite temperatures) QWIs was little studied. Comprehensive research in this area was urgenly needed.

1.2 Summary of Major Results

1. As a part of our research devoted to the development of the proper model of electron scattering in real QWIs we have calculated electron intra-subband and inter-subband scattering by confined LO and localized SO phonons in QWs and rectangular QWIs. These rates were included in our Monte Carlo programs, which allow for the multisubband structure of electron spectrum. We have performed preliminary simulations of electron transport, diffusion, and noise at high temperatures and in a wide range of electric fields. We have demonstrated that the role of LO phonon scattering is dominant in a wide range of sizes of LD structures. It is mainly responsible for electron momentum relaxation and defines transport parameters at room temperature. Electron noise at room and liquid nitrogen temperatures is also primarily controlled by LO phonon scattering. The SO phonons are also important in injected electron relaxation because there exist two branches of SO phonons with different energies. They, along with LO phonons, yield very

fast thermalization of nonequilibrium electron systems at room temperature. The LO phonons alone do not assure thermalization of electron gas because LO phonon dispersion is negligible and the cascade emission of LO phonons and their reabsorption does not lead to the energetic broadening of the peak-wise injected electron distribution.

2. We have investigated acoustic-phonon scattering. Our investigation has shown that many details of electron scattering, usually omitted in previous work come into effect in 1D structures and should be taken into account. The elasticity of electron-acoustic phonon scattering is a commonly used approximation. A closer look at this scattering mechanism shows that electron scattering by acoustic phonons in QWIs becomes essentially inelastic. This is due to the fact that the momentum conservation for electron-acoustic phonon systems is preserved only with an accuracy of $\pi\hbar/W$ where W is the effective thickness of the structure $W^{-2} = W_y^{-2} + W_z^{-2}$. For example, in GaAs quantum wire with $W_y = W_z = 40\mathring{A}$ the phonon energy corresponding to momentum $\pi\hbar/W$ is equal to 7.6 meV, i.e., this energy constitutes an essential part of the optical phonon energy. Thus, over a wide range of system parameters an electron can absorb or emit an acoustic phonon with energy comparable to its own. The electron-acoustic phonon scattering turns out to be essentially inelastic, and becomes an effective mechanism of energy dissipation. Moreover, the momentum conservation for electron transition from subband n to subband n' is satisfied only with an accuracy of $(n + n')\pi\hbar/W$. This results in even higher inelasticity of electron-acoustic phonon scattering, so that the long-wave approximation for acoustic phonon scattering breaks down. The complex nature of the overlap integral is responsible for details of the scattering rate for transitions inside higher subbands of a quantum wire and for considerable deviations from the $\epsilon^{-1/2}$ (where ϵ is electron kinetic energy) dependence of the scattering rate in 1D structures. We have included calculated acoustic phonon scattering rates in our Monte Carlo program and have found that in the absence of external excitations our calculations lead to an equilibrium Boltzmann distribution function. This shows that our treatment of acoustic phonon scattering complies with the detailed equilibrium principle. Summarizing, we have developed an adequate model of electron-acoustic phonon interaction suitable for incorporation in numerical programs for electron transport simulation in QWIs.

3. We have obtained comprehensive results on electron transport in QWIs in a wide range of electric fields and temperatures.

We have predicted and numerically obtained superlinear electron transport in QWIs at low temperatures. This superlinearity stems from reduction of acoustic phonon scattering efficiency when the electron system is heated. The mobility and diffusivity of electrons increase in the superlinear regime and then decrease as the optical phonon scattering starts dominating at higher electric fields. The electron distribution function in the superlinear regime can be characterized by two slopes corresponding to two different electron temperatures. We have calculated all the main kinetic coefficients and relaxation parameters that define device operation.

We have discovered a novel effect of negative absolute photoconductivity in QWIs. This effect is caused by strong asymmetry of the electron distribution function due to resonant scattering by optical phonons. The effect of negative absolute conductivity can

occur either in the transient regime of electron response to a step-like electric field pulse or in the steady state. In the latter case, the recombination plays a crucial role by eliminating thermalized electrons from the subband bottom. It has been demonstrated that the effect of negative absolute conductivity can serve not only as a mechanism of microwave generation but also as an indirect technique to experimentally investigate phonon confinement in a QWI.

We have investigated the role of different phonons on electron transport in QWIs and have searched for the optimum cross-sections from the viewpoint of high electron mobilities and low-noise performance. We have found that a transverse size ratio of 1:1 is optimum for high mobilities because the smaller size defines the intensity of the electron-phonon interaction and the larger size defines the number of occupied subbands. The cross-section of $150 \times 150 \mathring{A}^2$ is the optimum for high mobility. For this cross-section, the rates of electron scattering by localized surface optical phonons and acoustic phonons are already low, whereas there are just few subband occupied by electrons even at room temperature.

4. A crucial device characteristic is electric noise. Electric noise is commonly viewed by physicists as a limiting factor. It is desirable to create electronic and photonic devices with the lowest possible noise. This would allow one to reduce errors in information transmission through optical interconnect systems, and to increase the sensitivity of devices. QWIs present systems with few electrons, and thus electron noise in QWIs is essentially different from noise in bulk materials. We have for the first time calculated nonequilibrium electron noise in QWIs at low lattice temperatures in a wide range of electric fields. Our results show that a major noise source in QWIs is electron scattering by acoustic (low field) and optical (high field) phonons. The existence of several optical phonon modes in a QWI does not affect the noise behavior. In general, noise in QWIs is essentially suppressed. At room temperature low-frequency noise monotonously decreases when increasing the electric field. The similar trend is observed at low temperatures in very thin QWIs where acoustic phonon scattering is very effective. In rather thick QWIs at low temperatures the low-frequency noise initially increases when increasing the electric field due to reduction of acoustic phonon scattering efficiency. After that initial increase, the low-frequency noise starts decreasing due to onset of optical phonon scattering. The peaks associated with electron coherent motion appear on noise spectral density on streaming frequency and its higher harmonics. With further increase in electric field all noise collapses to these single frequencies. The noise at low and intermediate frequencies decreases with the decrease of cross-section of a QWI. Hence, the further suppression of low-frequency noise is possible by choosing the proper magnitude of electric field and cross-section of a QWI.

The comprehensive review of the results obtained during work on this project is given in Ph.D. dissertation of Dr. R. Mickevicius, which has been submitted to ARO.

Chronological List of Publications

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[A] Papers

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1.3 Participating Personel

1. Vladimir Mitin, PI.

2. Rimvydas Mickevičius, Graduate Research Assistant, earned Ph.D. in Electrical Engineering in December 1993. Since January 1994 Dr. Mickevičius has been working on the project as Visiting Assistant Professor.

3. Nikolai Bannov, Graduate Research Assistant, earned Ph.D. in Electrical Engineering in December 1994.

4. Yuri Sirenko, Graduate Research Assistant, earned Ph.D. in Electrical Engineering in December 1994.

5. Remigijus Gaska, Graduate Research Assistant, expected to graduate with Ph.D. in August 1995.

6. Lakshmi Narayana Kethamreddy, Graduate Research Assistant, earned M.S. in Electrical Engineering in December 1993.

7. Uma Harithsa. Graduate Research Assistant, expected to graduate with M.S. in April 1995.

2 INVENTIONS

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